INVESTIGATING SURFACE QUALITY OF AFRICAN MAHOGANY (*KHAYA IVORENSIS*) FROM GHANA USING STYLUS AND DEFLECTOMETRY TECHNIQUES

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(Received November 2014)

Abstract. Studies and information are limited on quantitative evaluation of machined surfaces of tropical African hardwood species such as mahogany (*Khaya ivorensis*). In this study, surface quality of mahogany from plantations and natural forests that were harvested near Pra-Anum Forest Reserve, Ghana was evaluated using the stylus profilometer and Optimap deflectometry techniques. The evaluation was made at three different height levels: bottom, middle, and top portions of harvested trees. The average roughness, mean roughness depth, maximum surface roughness, core roughness depth, reduced peak height, reduced valley depth, total height of roughness, and maximum depth of roughness motif were estimated on tangential surfaces of the samples after sanding using sandpaper of grit size P150, P180, and P 280. Texture values were also measured at different wavelengths using an optimap device. Based on the results of statistical analysis, the selected roughness parameters varied significantly at different portions of wood samples at 95% confidence level in both plantation and natural samples except reduced peak height parameter. Results also revealed that mean roughness parameters at the bottom and middle portions of the trees had relatively lower values in plantation samples than in natural samples. This implies smoother surfaces for the plantation samples. At the top portion, however, plantation samples had relatively higher values for most roughness parameters than did natural samples. Texture values at different wavelengths showed statistically significant variation along the stem for both natural and plantation samples at 95% confidence level. Although some limitations exist in using Gaussian amplitude filters to eliminate deep sinks in the profile, the data gave a good indication of surface quality and comparison of surfaces of mahogany samples.

Keywords: Surface quality, hardwood, mahogany, plantation wood, machined surface.

INTRODUCTION

Quality evaluation of wooden surfaces has been described as one of the most difficult issues in wood working research, and its mode of assessment has been the subject of great interest to researchers and consumers of wood products (Sandak and Negri 2005; Sinn et al 2009). The machined wood surface is a complex heterogeneous polymer composed of cellulose, hemicellulose, and lignin, and is influenced by several

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Wood and Fiber Science, 47(2), 2015, pp. 190-198

intrinsic factors of the material's morphology of polymers and other physical and chemical properties of wood as well as processing conditions. Properties inherent to wood, such as cell types and arrangement, porosity, density, and color variations, make measurement of surface roughness a challenge (Sandak et al 2003). This could be one of the reasons why there are no generally valid correlations to estimate surface roughness parameters as a function of influencing factors. Surface texture of machined surfaces of wood, as revealed by reaction to cutting tools which in turn is determined by size and proportional amounts of cells, especially the vessels, is an important wood quality when decorative and finishing processes of tropical wood are concerned.

Many studies have been undertaken on surface quality of solid wood and wood composites in past decades (Lemaster and Beall 1993; Mitchell and Lemaster 2002). According to Wengert and Lamb (1994), the planed surface characterization of solid wood is a function of machining quality. Some other surface quality researchers were dedicated to relationships between three-dimensional (3D) roughness parameters and machining parameters or gluing performance (Hernandez et al 2011; Fellin et al 2009; Cool and Hernandez 2011; Ramananantoandro et al 2014).

Generally, most natural tropical hardwood species are brown, cream (white), red, or shades of these three colors and are predominately medium density, although a few are of low or high density (Oteng-Amoako 2006). These species, such as mahogany, are commercially used for decorative furniture, boats and boat components, vehicle bodies, and decorative veneer for plywood making.

Scarcity of these valuable natural hardwood species and degradation of most tropical forests have led to the establishment of plantations. Worldwide, managed fast-growing forests have been steadily increasing and are expected to dominate the world's wood supply in the future. But, managed resources have been associated with a significant decline in wood quality (Zobel 1984; Kellogg 1989). These resources are usually characterized by younger age, smaller stem diameter, larger taper, larger knots, higher juvenile wood content, and different wood characteristics and processing properties compare with their natural counterparts. A combination of these factors of plantation trees could eventually influence the quality of the wood and finally the wood surface. However, quality may also be influenced within limits by sawing especially when the head saw is a band saw or a circular saw.

In the past, various physical phenomena such as mechanical, optical, pneumatic, ultrasonic, electric, or temperature detection approaches have been used as principal components for measuring wood surfaces (Shiraishi 1986; Riegel 1993; Thomas 1999). The appropriateness and applicability of these techniques vary significantly in industrial and laboratory conditions. The techniques most capable of determining surface roughness of materials such as metal, plastic, and wood in an industrial environment are those that are noncontact, with reproduction of the profile such as optical profilometers, microscopes, image analyzers, imaging spectrographs, interferometers, fiber–optic transducers, laser scatters, and optical light-sectioning systems. The contact process of measuring surface roughness, such as with the stylus profilometer, provides a more quantitative and hence more objective measure of the surface profile, although there are some limitations in the filtering process, especially in measuring tropical timber species with large vessel size (porous timber).

The stylus technique is the standard for roughness assessment of materials including metal, plastics, and wood surfaces. According to Kilic et al (2006), any kind of irregularity and magnitude of roughness on a surface can be objectively quantified by the stylus method. There are various modifications of this method, such as with or without a skid or varying stylus tips (geometry, materials). The stylus method has been used to determine surface roughness of solid wood in past studies (Hiziroglu 1996; Hiziroglu and Suchsland 1993; Mummery 1993). There are many advantages of using the stylus instrument for measuring the roughness of machined wood surfaces, such as the production of actual profile of surfaces and the ability to calculate different roughness parameters from the profile using different amplitude filters. This technique also has some important limitations, such as possible damage of the surface, nonzero tip radius, missing fine irregularities, cone angle of the tip, sliding on the steep fragments of the profile, and relative slowness. In recent years, several attempts have been made to overcome some of these limitations (Fujiwara 2004; Fujiwara et al 2001).

Although many studies have been done on the methods of evaluating surface quality of solid wood and the relationship between these techniques, little information exists on the quantitative assessment of decorative and valuable tropical African timber species and the comparison of techniques for assessing surface quality of wood obtained from natural and plantation forests. The objective of this study, therefore, was to evaluate the surface quality of machined surfaces of African mahogany from both natural and plantation forests using the stylus profilometer and deflectometry methods.

MATERIALS AND METHODS

Materials

Five mature trees of plantation-grown mahogany and three naturally grown mahogany trees were extracted from Amantia in the Pra-Anum Forest Reserve, Ghana. The location of the reserve is between latitude 6°11′ to 6°20′ north and longitude 1°07′ to 1°16′ west. The site is situated within the moist semideciduous (south-east) forest type in Ghana with a mean annual rainfall between 1500 and 1750 mm. Trees were harvested for the experiment in February 2012 using logging machinery from Log and Lumber Limited (LLL), Kumasi, Ghana. The logs were transported to LLL for primary processing where a vertical bandmill with a 203.2-mm-thick, 10.18-m-longsaw blade with gauge of 0.43 m without tipping was used. The saw blade was swage set for processing.

Sample Preparation

Thirty-six samples consisting of 18 each for plantation-grown and natural wood of mahogany with a dimension of 230 × 105 × 10.5 mm^3 were prepared and planed. The samples were then placed in a computer-controlled climate chamber at 20°C and 65% RHfor 2 wk. According to Kilic et al (2006), no significant difference existed between surface roughness characteristics of tangential and radial machined surfaces of wood samples at a 95% confidence level. The tangential surfaces of the test samples were sanded with a wide-belt sanding machine using sandpaper of grit sizes P150, P180, and P280 (aluminum oxide type). Cutting rate (V_c) was 18 m/s, and workpiece feed rate (V_f) was 12 m/s. Figure 1 shows the sanded samples. These machining parameters were kept constant for sanding of all samples. The sanded samples were then placed in the climate chamber before the measurement for surface profile analysis was made.

Data Collection

Stylus method. The stylus instrument used in this study was the Hommelwerke type with a tip type of TK300 (Fig 2). Measurements were taken with a 48-mm scan length with a Gaussian regression filter (DIN ISO 11562). Each sample of the mahogany was measured 10 times on the tangential surface. Figure 3 shows a typical

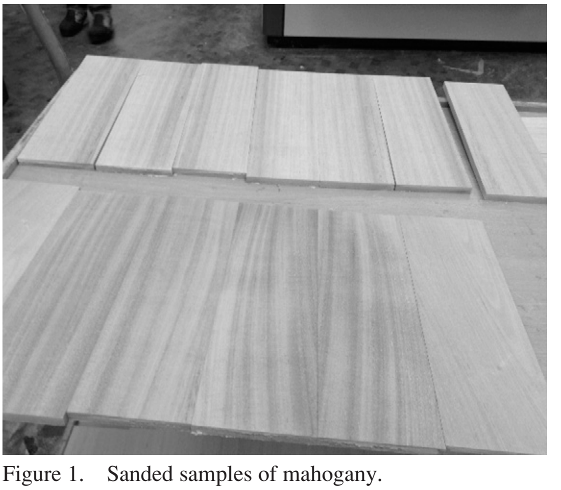

Figure 1. Sanded samples of mahogany.

Figure 2. Hommelwerke stylus instrument.

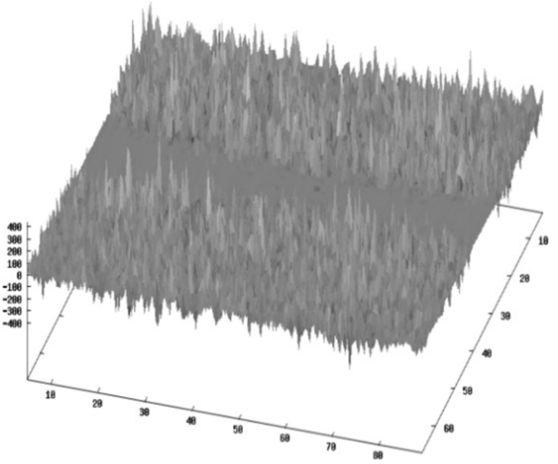

Figure 4. Three-dimensional representation of the surface of mahogany sample in $X + Y$ direction.

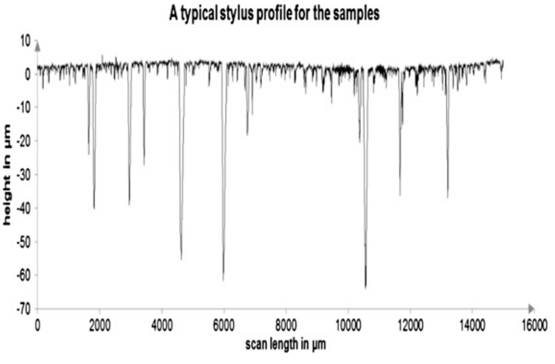

Figure 3. A typical profile of the *K. ivorensis* species.

profile from the stylus instrument. The roughness parameters, average roughness (R_a), mean peak to valley height (R_z), core roughness depth (R_k), reduced peak height (R_{pk}), reduced valley depth (R_{vk}), total height of roughness (R_t), maximum surface roughness (R_{max}), root mean square roughness (R_q), and maximum depth of roughness motif (R_x), were estimated on tangential surfaces of the wood samples.

Optimap deflectometry. The Optimap (Rhopoint Instruments, East Sussex, UK) uses an advanced measuring technique known as phase stepped deflectometry (PSD). It makes fast, objective, full-field measurements across large areas requiring no movement across the surface. In this study, configuration mode of extra dull and display mode of texture and multiband were applied. The device has a 1.3-megapixel camera with a 1296 × 966 image resolution. The measurement area was 95 × 70 mm^2 with a lateral resolution of 75 µm. Texture values were measured at different wavelengths (T_a = 0.1-0.3 mm, T_b = 0.3-1.0 mm, T_c = 1.0-3.0 mm, T_d = 3.0-10 mm, and T_e = 10-30 mm). Figure 4 shows a typical 3D representation of the surface of mahogany samples in the $X + Y$ direction.

RESULTS AND DISCUSSION

Roughness Parameters

Results of mean values for surface roughness parameters of the 36 sanded samples are presented in Table 1. As shown, the plantation samples recorded relatively lower mean roughness values than the natural ones at the bottom and middle portions of the stem but higher values at the top portion. This indicates that plantation samples had smoother surfaces than natural ones at the bottom and middle portions. For instance, mean roughness values for natural and plantation at the bottom portion were R_a (4.815, 3.722), R_q (9.95, 7.465), R_z (80.610, 62.96), and R_{vk} (27.345, 20.273). For the middle portions, a similar trend was recorded for all roughness values measured. The top portion, however,

Table 1. Mean roughness parameters of plantation-grown and naturally grown mahogany from Ghana.[a]

	Mahogany					
	Bottom		Middle		Top	
Roughness parameter[b]	Natural	Plantation	Natural	Plantation	Natural	Plantation
R_a (μm)	4.815 (0.590)	3.722 (0.503)	5.383 (0.649)	3.738 (0.436)	3.945 (0.532)	6.957 (0.781)
R_q (μm)	9.950 (1.128)	7.465 (1.00)	10.960 (1.072)	7.353 (0.784)	8.012 (1.099)	12.645 (1.226)
R_z (μm)	80.610 (8.534)	62.960 (6.944)	86.928 (7.362)	61.312 (6.078)	67.973 (9.017)	90.862 (7.690)
R_{max} (μm)	102.827 (12.039)	80.515 (11.592)	110.615 (11.0831)	77.230 (9.677)	89.485 (12.483)	112.557 (11.385)
R_{pk} (μm)	2.497 (0.275)	2.313 (0.209)	2.775 (0.266)	2.282 (0.256)	2.773 (0.378)	2.468 (0.396)
R_k (μm)	6.337 (0.276)	5.527 (0.256)	6.880 (0.325)	5.497 (0.255)	6.060 (0.286)	6.292 (0.286)
R_{vk} (μm)	27.345 (3.88)	20.273 (3.404)	30.422 (3.897)	20.193 (2.815)	20.743 (3.845)	36.105 (4.178)

[a] Standard deviation is given in parentheses.
[b] R_a, average roughness; R_q, root mean square roughness; R_z, mean roughness depth; R_{max}, maximum surface roughness; R_{pk}, reduced peak height; R_k, core roughness depth; R_{vk}, reduced valley depth.

showed a different trend for natural and plantation samples for all roughness values except for R_{pk} values (2.773, 2.468). Statistical analysis of the results revealed that there was no significant difference in the mean roughness parameters of natural and plantation samples at 95% confidence level. For instance, the statistical p values for roughness parameters R_a and R_{vk} were 0.9562 and 0.9434, respectively.

Figures 5 and 6 show the results of the surface roughness for naturally grown and plantation

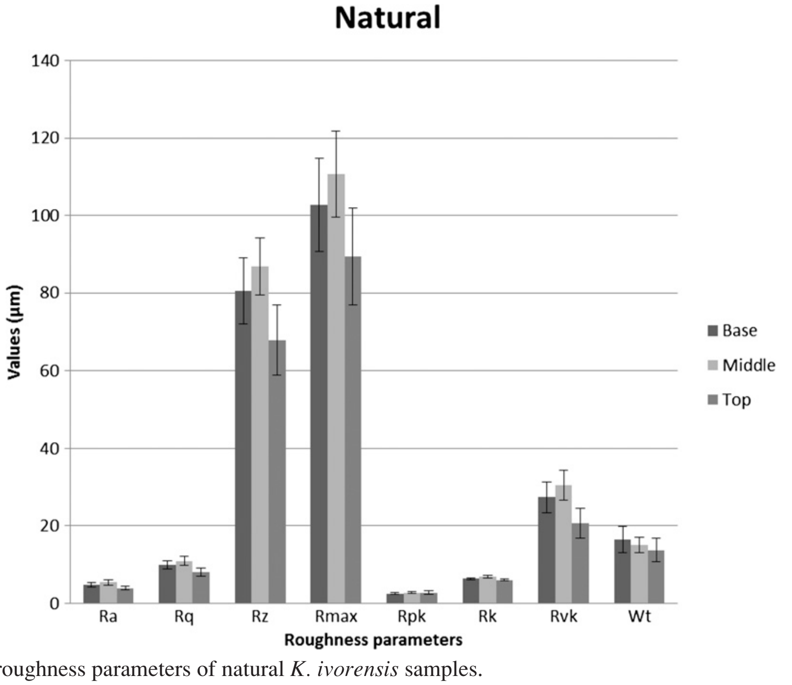

Figure 5. Mean roughness parameters of natural *K. ivorensis* samples.

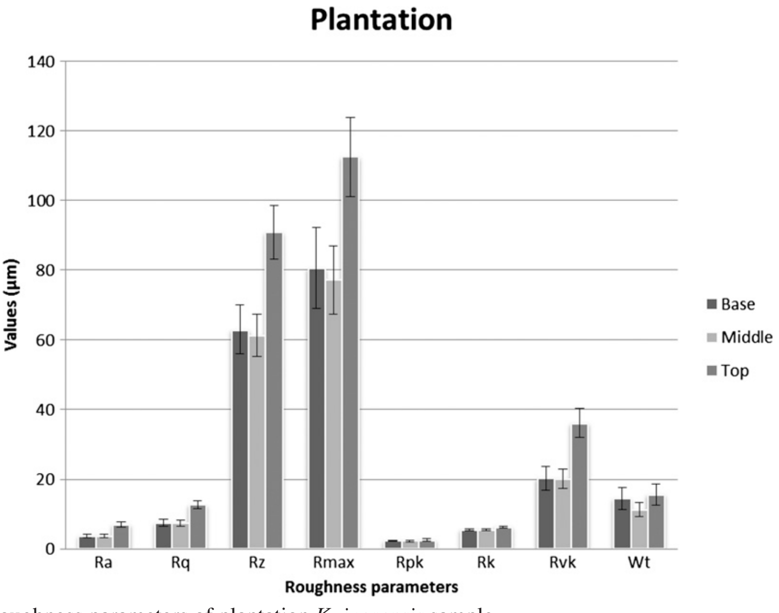

Figure 6. Mean roughness parameters of plantation *K. ivorensis* sample.

mahogany. In all roughness parameters, the top samples had relatively low values indicating a smoother surface than the other portions. Again, the bottom had lower values of R_a, R_q, R_z, and R_{max} than the middle portions of naturally grown mahogany. This may have been caused by the variation in some physical properties of the stem such as density and vessel sizes shown by R_{vk} values.

Table 2 shows statistical p values for the roughness parameters for the different parts of the samples. All roughness parameters except R_{pk} varied significantly at different portions of the samples of both natural and plantation samples at 95% confidence level.

Texture Measurement

Tables 3 and 4 show texture values in the X direction of the sanded samples of plantation-grown and naturally grown mahogany at the different wavelengths. No regular trend was recorded for the mean value samples at different height levels in both natural and plantation samples.

Based on statistical analysis of the results shown in Tables 5 and 6, there was significant variation in the texture values at different height levels. Significant variation also existed in the different height levels of the samples. The results relate to the variation recorded in the roughness parameters in this study. Hendarto et al (2006) proposed

Table 2. Statistical p-values for roughness parameters of natural and plantation samples.

Roughness parameter[a]	p-value			
	Natural	Remarks	Plantation	Remarks
R_a	0.000746	Significant	3.11E-09	
R_q	0.000161	Significant	1.07E-09	
R_z	0.000123	Significant	2.69E-09	
R_{pk}	0.304067	Not significant	0.22	Not significant
R_k	0.03970	Significant	0.00023	
R_{vk}	3.12E-05	Very significant	3.34E-09	

[a] R_a, average roughness; R_q, root mean square roughness; R_z, mean roughness depth; R_{pk}, reduced peak height; R_k, core roughness depth; R_{vk}, reduced valley depth.

Table 3. Texture values for plantation-grown mahogany at different wavelengths.

	Plantation	X direction				
	T	T_a	T_b	T_c	T_d	T_e
Bottom	15	370	130	120	250	800
	68	240	130	120	240	640
	45	370	120	110	200	420
	73	370	93	100	160	480
	31	300	110	110	210	650
	36	340	120	110	220	660
Average	44.6667	331.667	117.167	111.667	213.333	608.333
SD	22.3129	52.6941	14.006	7.52773	32.0416	137.174
Middle	90	410	85	99	160	440
	97	430	83	100	170	500
	80	400	99	110	170	330
	83	400	97	110	170	380
	97	430	82	99	160	550
	68	370	100	110	180	370
Average	85.8333	406.667	91	104.667	168.333	428.333
SD	11.1967	22.5093	8.50882	5.85377	7.52773	84.2417
Top	25	230	93	100	200	540
	68	340	90	100	210	460
	42	290	100	100	200	490
	37	280	100	100	200	520
	36	240	89	100	190	640
	37	360	100	100	200	550
Average	40.8333	290	95.3333	100	200	533.333
SD	14.4418	52.1536	5.27889	0	7.07107	61.8601

SD, standard deviation.

Table 4. Texture values for natural samples in the *X* direction at different wavelengths.

	Natural	X direction				
	T	T_a	T_b	T_c	T_d	T_e
Middle	73	440	120	120	260	540
	40	310	130	120	290	490
	64	430	120	120	280	670
	62	400	120	110	250	540
	72	430	120	120	260	630
	27	360	130	120	260	610
Average	56.3333	395	123.333	118.333	266.667	580
SD	18.6619	50.892	5.16398	4.08248	15.0555	67.5278
Bottom	64	360	100	110	160	490
	42	330	110	110	170	530
	34	330	120	110	170	380
	84	390	89	100	170	470
	63	370	110	110	160	470
	66	360	100	110	180	370
Average	58.8333	356.667	104.833	108.333	168.333	451.667
SD	18.049	23.3809	10.7781	4.08248	7.52773	63.3772
Top	40	290	100	100	200	420
	36	390	130	110	210	600
	90	470	120	110	200	690
	75	480	130	120	200	850
	69	340	92	97	190	450
	72	360	92	98	200	410
Average	63.6667	388.333	110.667	105.833	200	570
SD	21.1912	74.6771	18.1402	9.04249	6.32456	176.748

SD, standard deviation.

Table 5. ANOVA—texture values for plantation samples.

Source of variation	SS	df	MS	*F*	*p*-value	*F* crit
Sample	16,268.74	2	8134.37	3.844439	0.024997	3.097698
Columns	2,907,758	5	581,551.6	274.851	6.63E-53	2.315689
Interaction	140,429.7	10	14,042.97	6.636942	1.24E-07	1.937567
Within	190,429.2	90	2115.88			
Total	3,254,885	107				

ANOVA, analysis of variance.

Table 6. ANOVA—texture values for natural samples.

Source of variation	SS	df	MS	*F*	*p*-value	*F* crit
Sample	43,650.8	2	21,825.4	7.76959	0.000771	3.097698
Columns	3,095,640	5	619,128	220.4024	6.8E-49	2.315689
Interaction	54,525.54	10	5,452.554	1.941046	0.04954	1.937567
Within	252,817.2	90	2,809.08			
Total	3,446,634	107				

ANOVA, analysis of variance.

a new approach to overcome the shortcoming in measured profiles, such as artificial peak (push up), and provide a more accurate and reliable timber roughness analysis method.

CONCLUSIONS

Tropical hardwood species such as mahogany have characteristics that make them suitable for commercial uses. In this study, evaluation of the machined wooden surface using the stylus profilometer was aimed at estimating differences between the samples of natural and plantation-grown wood. Based on statistical analysis, no significant difference was observed between surface roughness parameters of plantation and natural samples at 95% confidence level. Further analysis, however, indicated that there was significant variation in the roughness parameters within tree species at different height levels measured at 95% confidence level at the three height levels for both natural and plantation samples. In the use of plantation samples for industrial purposes, much effort is needed during machining to ensure that tropical timber species are well processed for better surface quality. Further work on the filtering process such as the use of robust filtering methods is necessary to eliminate the effect of artificial peaks that might be related to the use of Gaussian filters.

ACKNOWLEDGMENTS

The authors express special thanks to The World Academy of Science (TWAS) and German Research Foundation (DFG) for the financial support through the TWAS-DFG Cooperation visits for Scientists from Sub-Saharan African program. Special thanks to Andrea Huxol and Nandeesh Nagaiah of the Hochschule Ostwestfalen-Lippe, University of Applied Science, and Lemgo, Germany, for their kind assistance. Many thanks go to the Director of CSIR-Forestry Research Institute of Ghana, Dr. Victor Agyeman, for his support and also Dr. E. Opuni-Frimpong, the project coordinator of International Tropical Timber Organization (ITTO) Mahogany project, for the mahogany samples for the research work.

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